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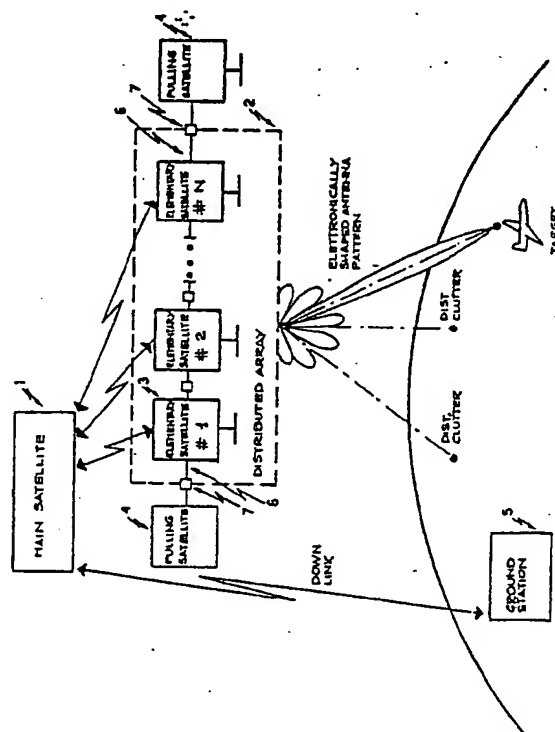
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DE FR GB NL SE(71) Applicant: SELENIA SPAZIO S.p.A.
via Pile 3
I-67100 L'Aquila(IT)(72) Inventor: Galati, Gaspare
Via C. Corvisieri 22
I-00162 Roma(IT)
Inventor: Lo Squadro, Giacinto
Via Igino Giordani, 60
I-00155 Roma(IT)(74) Representative: Gustorf, Gerhard, Dipl.-Ing.
Patentanwalt Dipl.-Ing. Gerhard Gustorf
Mühlenstrasse 1
D-8300 Landshut(DE)

(54) Radar system consisting of an array of interconnected elementary satellites.

(57) Radar system for primary and secondary air-space surveillance, and more exactly for the detection and tracking of moving targets, consisting of a number of elementary satellites connected to non rigid structures and of a main satellite, which performs accurate measurement of the position and altitude of elementary satellites and real time adaptive combination of radar signals coming from them, so as to provide a large phased array operating in the microwave band. Such system overcomes the limitations on dimensions of large space-borne antennae found in literature, minimizing the incidence and effects of undesired echoes and interference & assuring high detection accuracy. The fact that the elementary satellites are all the same (modular) makes possible gradual assembly of the system with possible expansion in time and assures particularly high operating availability.



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Radar system consisting of an array of interconnected elementary satellites

This invention belongs to the field of primary and secondary surveillance radars which are meant to detect mobile targets (such as aircraft), measure their present position, predict their future position and finally, as far as possible, identify them. It is a well known fact that radar surveillance is applied to the Civil (e.g. as an Air Traffic Aid) and military field (e.g. defence of the airspace). The coverage of a ground based surveillance system is limited by the horizon and by orographic constraints, particularly at relatively low altitude; a spaceborne system, by utilising artificial satellites, is not affected by such limitations and can cover a very large area and distribute surveillance data to many users. The main functional and operating characteristics of air-space radar surveillance, to date at an early definition stage, are highlighted in a few recent publications, such as:

[1] W.J. Cairne "Space-based radar application to Air Traffic Control", IEEE Internal. Radar Conference, Arlington, May 6-9, 1985 (IEEE Cat No 85 CH 2076-8), pp 312-321.

[2] E. Brooknes: "Derivation of a satellite radar architecture for air surveillance", IEEE Eascon - 1983 (IEEE Cat. No. 0531-6863/83), pp 465-475.

[3] G. Galati, G. Losquadro "Space-based multifunction radar systems: future tool for civilian and military surveillance 42nd Symposium of the Guidance & Control Panel of the AGARD, Bruxelles, 10-13 June 1986, pp 31.1-31.9.

As highlighted in article 3 above, radar surveillance systems may use the primary, the secondary, or both, radars. The characteristics and operation of the primary & secondary radar, which are standard systems used by the International Civil Aviation, are well known to the relevant experts and operators.

Space borne surveillance cannot be performed by simply carrying present techniques and technologies of primary and secondary radars on board artificial satellites because of two types of problems, both due to the very large distance (in the order of thousands of kilometers) between the radar antenna and the targets to be detected.

The first problem is that of the power required to be transmitted, particularly high for the primary radar, because the product of the square of the antenna effective area and power transmitted is proportional to the fourth power of range.

Therefore the need arises for a high power transmitter and for an antenna with a very large effective area, or in other terms, having high gain.

The second problem is that of the very high angle accuracy required to achieve accurate loca-

tion at long range, comparable to that achievable with groundbased systems operating at much shorter ranges. This last requirement too needs an antenna with a very narrow main lobe, and therefore very high gain. The dimensions of antennae with such performance are particularly large (from a few hundred to a few thousand times) compared to the radar operating wavelength. This is set by operating and mission requirements for the primary radar, typically between 10 and 25 cm, and by International Civil Aviation rules for secondary radars, known as SSRs, set at 27.5 cm and 29.1 cm. Previous techniques attempted to solve, at least partly, these problems by means of physically large antennae, unfoldable in space in differing configurations. Mechanical and electrical aspects make the use of such antennae very critical and pose a limit to the maximum dimensions obtainable, fixed at few tens of meters per side, which does not provide complete satisfaction of the requirement.

This invention overcomes such limitations by means of a radically innovative concept; the invention is based upon a given number of modules orbiting around the Earth, called elementary satellites, each operating as an element of a phased array having very large dimensions. Each elementary satellite is provided with an antenna, a transponder and a communications subsystem interfacing the main satellite. The latter, which may be duplicated to increase the availability of the entire system, provides for coherent combination of the radar signals coming from the various elementary satellites, and this way an antenna with a radiating pattern having a very narrow main beam is obtained, comparable with that of a physical antenna with the same area occupied by the elementary satellites. This way a distributed array antenna is obtained, suitable for primary and secondary radars. The application, at least at the conceptual level, of the distributed array concept to the primary radar, with reference to the multistatic case, where transmitters and receivers are located at different points, is described in a recently published work:

[4] R.C. Hermiller, J.E. Belyea, P.G. Tomlinson: "Distributed Array Radar", IEEE Transactions on Aerospace & Electronic Systems Vol. AES-19 No. 6 November 1983, pp 831-839.

For application to Air Space Surveillance, monostatic operation is preferred (see [2] as an example) and a much larger than unity ratio (of the order of 100 : 1) between array area (i.e. the area over which the elementary satellites are distributed) and the sum of the areas of the array elements is required; under such conditions the concept of

distributed array as shown in [4] is not conveniently applied, as it would give way to an excessive degradation of the undesired lobes of the resulting radiating pattern. Such lobes are mainly a consequence of the thinned array, i.e. because the ratio of the areas above is much greater than unity. This invention eliminates such obstacle by relying upon the concept, well known to experts in array antennae and in systems using them, that the radiating pattern of an array is the product of an element factor (radiating pattern of the single element of the array) with an array factor (which is a function of the number and location of elements in the array alone). With previous state of the art, the array elements were very simple (such as dipoles) and their radiating pattern, almost constant within a wide angle, was not predictable. On the contrary, the elements used in this invention are complex antennae, which may also preferably be made by phased arrays, or at least having predictable radiating patterns. Such elementary antennae can direct the beam (the main lobe of their radiating pattern) in an assigned direction and: a) can generate adaptively very low gain values (so called nulls of the radiating pattern) in a number of assigned directions, about equal to the number of elementary radiators making up the antenna, preferably outside the main beam; or (6) may have very low gain values in all directions outside the main lobe.

To attenuate, or as commonly said, to suppress the undesired lobes within the main lobe of the elementary satellite antenna (and therefore of the element of the distributed array) this invention makes use of the concept of adaptive generation also at the distributed array level.

The adaptive generation of nulls concept and, more generally, adaptive shaping of an antenna radiating pattern, is described in many papers, among which the following:

[5] J.W.R. Griffiths "Adaptive Array Processing A Tutorial" IEEE Proceedings Vol. 130, Pts F and H, No 1, February 1985 pp. 3-10.

In this invention, the decision on which undesired lobes to suppress is taken by the main satellite processor on the basis of the following data:

a) Ratio between the level of each lobe and the level of the main lobe of the radiating diagram of the distributed array.

b) Reflectivity of the position of Earth surface regarded by each lobe (clutter map).

c) Geometry (range and dimension) of the radar resolution cells which regard the surface areas above.

Such information is contained in the main satellite control computer; that of item a) is measured periodically on the ground through measurement of one way radiating pattern, while items b) and c) are

updated on board by a calibration device, consisting of two sections: a passive section utilising transmitters at known locations on the surface of the Earth and in the frequency bands in which the space borne radar system operates, providing accurate geometric calibration, and an active section, which measures the level of the radio echo (clutter signal) coming from various positions of the surface of the Earth.

A further datum which the central computer of the main satellite needs to generate the radiation pattern of the distributed array, is the geometry of the array itself. Such geometry is controlled, within tight tolerance, by a non rigid structure, preferably implemented by wire, which prevents the elementary satellites from dispersing due to effects of various origin (differences in orbit velocity and gravitational field, solar wind etc.). Suitable dampers limit structure oscillations. The elementary satellites are mechanically connected to such structure, which takes the shape of a flat network which is kept under tension through suitable satellites, called "pulling satellites", equal in number to the vertexes of the polygon encompassing the network. The main satellite is preferably sited on the axis perpendicular to the network plane and mechanically attached to it (preferably by wire); it may also operate as a self pulling satellite. The satellite pulling forces and their resulting momentum are null, or such as to make the required corrections to the orbit and/or system attitude.

Such control is centralised on the main satellite, where the entire system geometry is known at all times. Accurate satellite position measurement, by the main satellite, is obtained preferably by means of laser telemeter as described in the following.

Each elementary or pulling satellite has three laser retroreflectors, i.e. plates of a material which has a much higher reflecting capacity than the rest of the satellite surface. A laser telemeter, built according to the criteria well known to the experts and fitted to the main satellite, is aimed onto the retroreflectors so as to provide three extremely accurate range measurements, from which the on board computer can obtain position and attitude of each elementary satellite. Aiming of the laser telemeter is facilitated by using the angle of the elementary or pulling satellite and the main satellite, the latter obtained through the measurement of the angles of arrival of the communications subsystem carrier between satellites (inter-satellite link). In one of the preferred implementations of this invention, such subsystem is optical; the theory and applications of optical techniques and technologies for data transmission are illustrated in many works, among which the well known:

[6] R.M. Gagliardi, S. Karp: Optical Communications, J. Wiley & Sons, 1975.

However their use for radar signal transmission in space does not appear to be described in literature. The advantages of optical transmission, preferably by means of laser are:

- very high directivity
- extremely wide band (channel capacity)
- reduced weight and dimensions.

Within this invention, the inter-satellite link provides exchange of the following data (as a non limiting example):

- From main satellite to elementary satellite:
 - a1) Waveform to be transmitter;
 - a2) Commands for active beam forming;
 - a3) Auxiliary signals and data (for synchronization, control & satellite functional check).
- From elementary satellite to main satellite:
 - b1) Radar echo (and/or SSR reply)
 - b2) Status and diagnostics data
- From main satellite to pulling satellite: data for orbit and attitude control.
- From pulling satellite to main satellite: status and diagnostic data.

A further implementation of this invention makes use of a conventional radio link, at the same radar frequencies or at shifted or submultiple frequencies, to transmit the waveform which (following multiplication or frequency shift) is amplified and phase shifted in the elementary satellites; the radio link may also be used in this configuration, for the data at a2) and a3). The secondary satellite radio receiver antenna has a sufficiently high directivity and front to back ratio to avoid that the radio transmission is affected by the radar signal transmitted when a sub multiple of the radar frequency is not used. This way, the combination of radar signals coming from elementary satellites is suitably implemented in radio frequency terms at antenna level. Finally, the main satellite is equipped with a data link operating toward one or more ground stations for the exchange of data required for control and calibration and for transmission toward ground of the radar data, processed to the most suitable degree.

Such link may be implemented using the most conventional techniques. In the best preferred form, radar data is processed on board, so that the "track messages" are transmitted toward ground, including therefore position, speed and possible auxiliary information related to the targets observed.

A further implementation of this invention processes the radar signal and extracts information within the ground station; this does not modify the peculiar characteristics and operation of the invention if not for a greater capacity of the transmitting link toward ground, however compatible with the

present state of the art.

This invention may be used for primary, secondary and both radar surveillance; furthermore it may be used for the selective type of secondary radar, known as SSR Mode S, which, further to the surveillance function, carries out that of data transmission toward and from surveilled aircraft, as well known to experts and users of radar surveillance and of air traffic control systems.

This invention, in one of its forms of implementation, makes use of the well known monopulse technique to improve angle measurement accuracy, especially under the condition of very low number of radar echoes or SSR replies coming from each target.

This situation is particularly true for the above mentioned SSR Mode S.

This invention will now be described with reference to one of its presently preferred forms of implementation, which is reported as a non limiting example and with reference to the figures and drawings attached, where:

Figure 1 shows the Spaceborne Surveillance Radar in its preferred general functional configuration:

1. Main satellite
2. Distributed array
3. Elementary satellite
4. Pulling satellite
5. Ground Station
6. Segment of the connecting structure
7. Damping element of the connecting structure.

Figure 2 shows the same system in its preferred general configuration and in simplified perspective view.

Figure 3 shows the main satellite in its preferred general configuration:

8. Receiver & Transmitter for the exchange of data with the ground station.
9. Radar data extractor
10. Processing of radar signal
11. Decoder
12. Primary power source and power supplies
13. Central Computer
14. Central Computer memory and stored maps
15. Stable Oscillator
16. Measurement device of the angle coordinates of the elementary satellites and pulling satellites.
17. Receiver of the inter satellite sub-system in the preferred optical configuration.
18. Ion motors and other actuators for orbit and attitude control.
19. Orbit and Attitude Control Unit

20. Laser aiming device used for telemetry

21. Laser telemeter

22. Processor for antenna beamforming

23. Processor for position and attitude of elementary and pulling satellites.

24. Processor for orbit and attitude control of the whole system.

25. Generator of system radiation pattern commands.

26. Generator of controls and synchronization of elementary satellites (radar part).

27. Coder of information to be transmitted

28. Transmitter subsystem between satellites; in the preferred implementation, of the optical type.

29. Processor for radar system management.

30. Radar waveform generator.

Figure 4 shows an elementary satellite in its preferred general configuration:

31. Antenna pattern forming network

32. Antenna, in the preferred phase array configuration including receiver and transmitter.

33. Laser retroreflector

34. Processor for status and diagnostic management for the various parts of the satellite.

35. Antenna pattern control unit

36. Received signal decoder

37. Radar transmission driver.

Figure 5 finally shows a pulling satellite in its preferred general configuration. Such satellite includes functional blocks identical to those present in the other satellites shown above, and in addition block (38) which is an orbit and attitude control which is managed by the main satellite.

This invention will now be described according to its general operating principle.

Depending upon the operating mode selected by the central computer (13) of the main satellite (1) (Figure 3), the management processor (29) of the radar system sends suitable commands to the controls and synchronisms generator (26) and to the transmitted waveform generator (30); controls, synchronisms and waveforms are coded and transmitted to all elementary satellites, simultaneously. In parallel, as a function of surveillance requirements and of the related environment, the central computer (13) sets the aiming direction of the beam; furthermore as a function of data a), b) and c) described in the first part of this application, contained in memory (14), the central computer (13) establishes the strategy for the suppression of sidelobes. Such data (pointing direction and suppression strategy) are sent to processor (22) which also receives precise information on elementary satellite position from processor (23). On the basis of such information, processor (22) calculates the

coefficients required for beamforming, converted into suitable commands by generator (25), coded by coder (27) and sent to such elementary satellites by transmitter (28). Receiver (17) of each elementary satellite (Figure 4) sends such commands, decoded by decoder (36), to another control unit (35) which completes processing and actuates commands acting upon the beamforming network (31) adapting the phased array in transmission and in reception.

During transmission, the waveform is decoded (36), suitably amplified by the so called transmitter driver (37) and sent to the transmitter section of the antenna (32). Later on, the radar echo (and/or SSR reply) coming from the target is received by antenna (32) of each elementary satellite, where the radiation pattern is formed by network (31); the resulting radar signal is coded by coder (27) and transmitted to the main satellite by transmitter (28), which, in the preferred implementation, is of the optical type. Such signal is received by receiver (17) (which is also of the optical type in the preferred form of implementation) (Figure 3) and sent to decoder (11) which uses the reference oscillation of the same stable oscillator (15) used for transmission coding in coder (27). The decoded radar signal is then transferred to processor (10) where noise filtering takes place (so called matched filtering or close approximation thereof), or that of different types of interference, firstly that of so called clutter undesired returns.

In the preferred form of implementation of this invention, within signal processing block (10) also the combination of signals coming from various elementary satellites takes place (spatial filtering, which synthesizes the distributed array). Such combination, in another form of implementation, takes place at radiofrequency level at the antenna which forms part of the electronic receiver, (17) in Figure 3.

The data of interest to operation, relevant to targets, is obtained from the extractor (9) by means of further filtering of the radar information coming from processor (10) and later transferred to the ground station by means of subsystem (8). Through the same subsystem (8) the information needed for beamforming and radar system management reaches the main computer (13); the latter, which includes type of waveform, controls and synchronisms, is processed by the management processor (29) which drives the controls and synchronisms generator (26) and waveform generator (30), the outputs of which are coded and transmitted to the elementary satellites by blocks (27) and (28).

Accurate knowledge of the distributed array geometry is obtained by means of a telemetry subsystem, which, in its preferred form of imple-

mentation, is of the laser type, where a laser telemeter (21) fitted on the main satellite is pointed onto suitable laser retroreflectors (33) fitted to each elementary and pulling satellite; pointing is aided by an angle measurement device (16) which uses the output of receivers (17) to measure the angle of arrival of the signal transmitted by the satellite and therefore also its angle position. The range measurements made by the laser telemeter (21) together with the angles provided by unit (16) are processed by computer (23) which determines the attitude of system satellites; such data is further processed to obtain the orbit and attitude corrections which are coded (27) and transmitted (28) to the pulling satellites, where they are received by receiver (17) and used by the orbit and attitude control system managed by the main satellite, block (38) which actuates them. The same position and attitude data is sent to the beam forming processor (22) where, as seen above, they are used to calculate the coefficients required for adaptive beamforming.

The distributed beamforming is calibrated exploiting the radar echoes of particular points on the Earth surface (known high reflectivity points) and using the replies sent by suitable SSR transponders set at well known positions. The difference between known position (stored in main computer (13)) and that measured by the radar system and transferred by extractor (9) to computer (13), is utilized by the same computer (13) to generate the correction commands, which are sent to the antenna beamforming processor (22). The difference between echo and reply amplitude and the related expected value may also be used, in a very similar manner, to check possible defocussing of the phased array and to perform the required corrections.

The main satellite has its own orbit and attitude control (19) with related actuators (18) as well as the orbit and attitude control processor of the entire system (24) which, by means of coder (27) and transmitter (28) sends control signals to each pulling satellite, where such signals are received by receiver (7) (Figure 5), which is optical, in the preferred implementation, and sent to the orbit and attitude control subsystem (38).

All satellites are equipped with their own electrical power supply subsystem, which includes a primary power source (12) (preferably implemented by means of solar panels and batteries) and supplies for all on board users.

Finally, the elementary and pulling satellites can transfer to the main satellite the information related to status and possible malfunctions (diagnostics), which are before hand processed and coded by a suitable processor (34).

Claims

Claim 1 Radar system for primary and secondary surveillance of the airspace, characterized by the fact that it is made up of more than one elementary satellite (3) operating as element of a distributed array and transmitting radar signals to a main satellite (1) where such signals are processed and further transmitted to a ground station (5).

Claim 2 Radar system as per claim 1, where the elementary satellites are interconnected by a non rigid structure (2) with segments (6) which are kept under tension and dampers (7), kept in balance by suitable pulling satellites (4) equipped with attitude and orbit controls managed by the main satellite.

Claim 3 Radar system as per claim 2, which, in one of its implementations, uses the main satellite (1) as a pulling satellite.

Claim 4 Radar system as per claims 1 & 2 above, where radar signals coming from elementary satellites are combined coherently and adaptively, so as to synthesize a phased array, and where the coefficients of such combination are calculated by a processor (which may be made up of a central computer (13), an antenna beamforming processor (22) and beamforming commands generator (25)) to attenuate the sidelobes and maximise the signal to noise ratio.

Claim 5 Radar system as per claims 1, 2 and 4 above, where each elementary satellite has an antenna (32) which is preferably a phased array, with coefficients determined on the basis of commands coming from main satellite (1) with the purpose to attenuate sidelobes and maximize signal to noise ratio.

Claim 6 Radar system as per claims 1, 2, 4, 5 above where an accurate measurement device of position and attitude of the elementary satellites is set on the main satellite and has the task to calculate the coefficients described at claims 4 & 5 by means of an antenna beamforming processor (22) and to transmit them, following coding (27) and by means of transmitter (28), preferably of the optical type, to the elementary satellites.

Claim 7 Radar system as per claims 1, 2, 4, 5, 6 above, where a subsystem for pulling satellites position accurate measurement (4) is fitted on board the main satellite with the purpose to provide it with orbit and attitude control of the entire system by means of a suitable processor (24) and with transmission of commands & controls generated by the latter, by means of a coder (27) and a transmitter (28), toward the orbit and attitude control subsystem (38) of the pulling satellites, driving suitable actuators (18) which include, preferably, ion motors.

Claim 8 Radar system as per claim 7 above, where the position measurement subsystem includes, without being limited to, a laser telemeter (21), an angle measurement unit (16) which helps to point the laser telemeter and a position computer (23) and also laser retroreflectors (33) preferably three in number, on each elementary and pulling satellite.

Claim 9 Radar system as per previous claims 1, 2, 4, 5, 6 and 7, where in the preferred implementation, the exchange of signals and data between main satellite and pulling & elementary satellites is performed optically by means of suitable transmitters (28), receivers (17), coders (27) and decoders (36).

Claim 10 Radar system as per previous claims 1,2,4,5,6,7 and 8 where in one of its implementations, the exchange of signals and data between main satellite and elementary and pulling ones is carried out by radio, and where the radar signals coming from targets are transmitted by elementary satellites to the main one, thereafter combined by the receiver antenna which makes up block (17) of main satellite (1).

Claim 11 Radar system as per claims 1,2,4,5,6,7,8 and 10 above, where the transmission of radar signals from elementary satellites to the main satellite as per claim 10, may be implemented at the same frequency at which the radar signals are received by the secondary satellites, or at a multiple or submultiple or at a shifted value of such frequency. The second implementation uses a shift or multiplication/division of frequency within receiver (17) and transmitter (28) of the elementary satellite.

Claim 12 Radar system as per claims 1,2,4,5,6,7,8,10, where the central computer (13) of main satellite (1) stores in its memory (14) the following data (as a non limiting example):

1) Ratio between sidelobes and peak of the distributed array.

2) Reflectivity of the surface of the earth covered by the array radiation pattern.

3) Geometry of the radar resolution cells of interest: such data is periodically updated by the main computer on the basis of measurements from ground through receiver (8) and utilized to calculate the coefficients as per claims 4 & 5.

Claim 13 Radar system as per claims 1,2,4,5,6,7,8,9,12 above, where in one of its implementations, the combination of radar signals coming from elementary satellites is performed by suitable coefficients which synthesize the monopulse radiation patterns to improve the accuracy of the angle measurement.

Claim 14 Radar system as per claims 1,2,4,5,6,7,8,9,12,13 where in one of its implementations, the radar signal processor (10) and data extractor (9) are housed in the ground station (5) rather than in the main satellite (1).

Claim 15 Radar system as per claims 1,2,4,5,6,7,8,9,12,13 where the radar echoes of particular portions of the surface of the Earth and the SSR replies of particular transponders set at known sites are used to achieve continuous calibration through which the beam pointing errors and possible defocussing are corrected.

Claim 16 Radar System as per Claims above, which may be used for primary/secondary radar surveillance and for defence or civil applications, including the selective secondary radar (SSR Mode S) and its numeric data link.

Claim 17 Radar system as per Claims above which may operate from low (altitude from one to few thousand Km) or high or geostationary orbits.

Claim 18 Primary and/or Secondary airspace surveillance radar which may be made up of a group of systems as described in the claims above, each located in a suitable orbit so as to assure continuous surveillance of an area of interest or global coverage.

Claim 19 Radar system for airspace surveillance from space, where the group of systems described in Claim 18 may be managed by a group main satellite, operating in the same manner as the system main satellite as described in Claims 1 to 15 above.

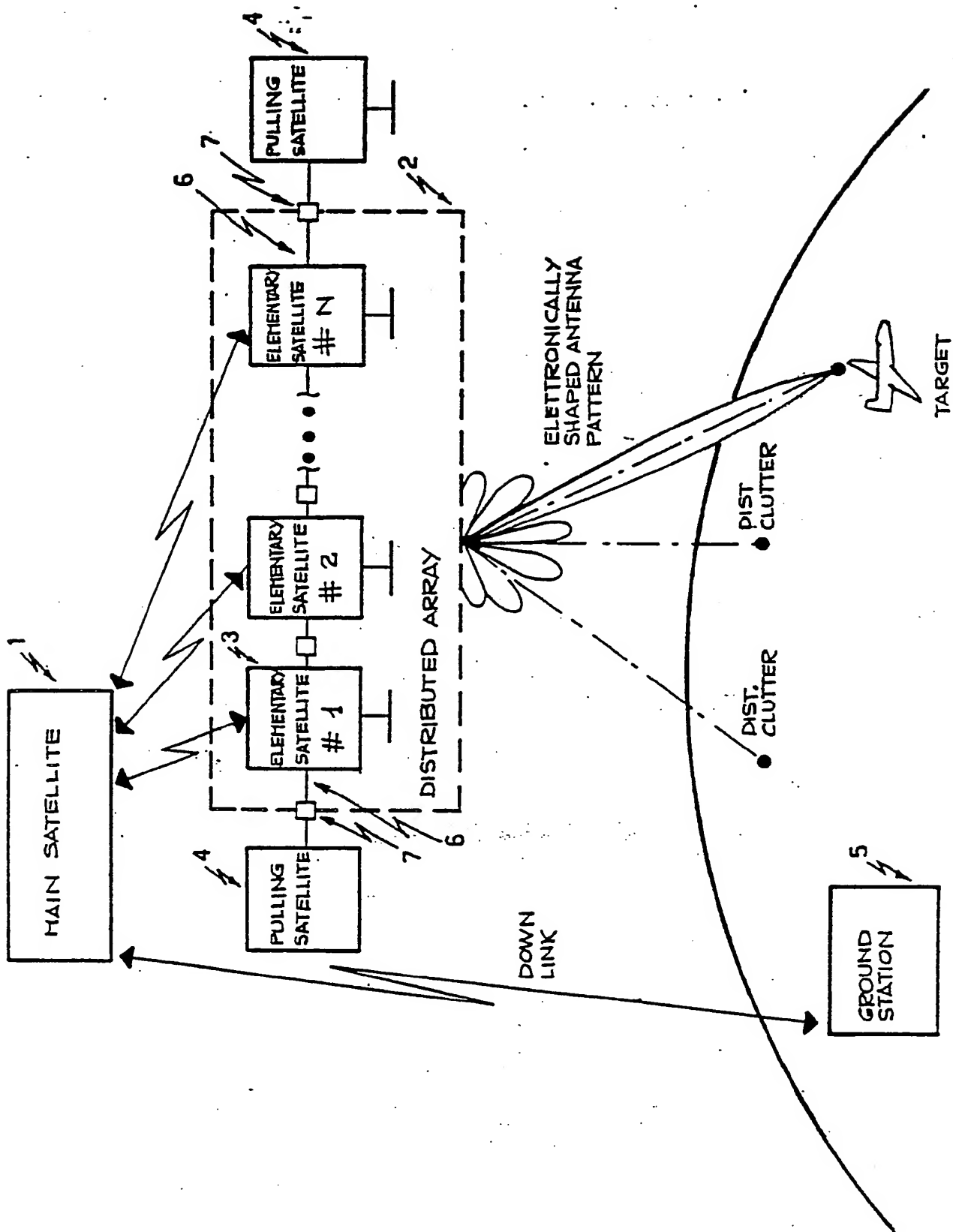


FIG. 1

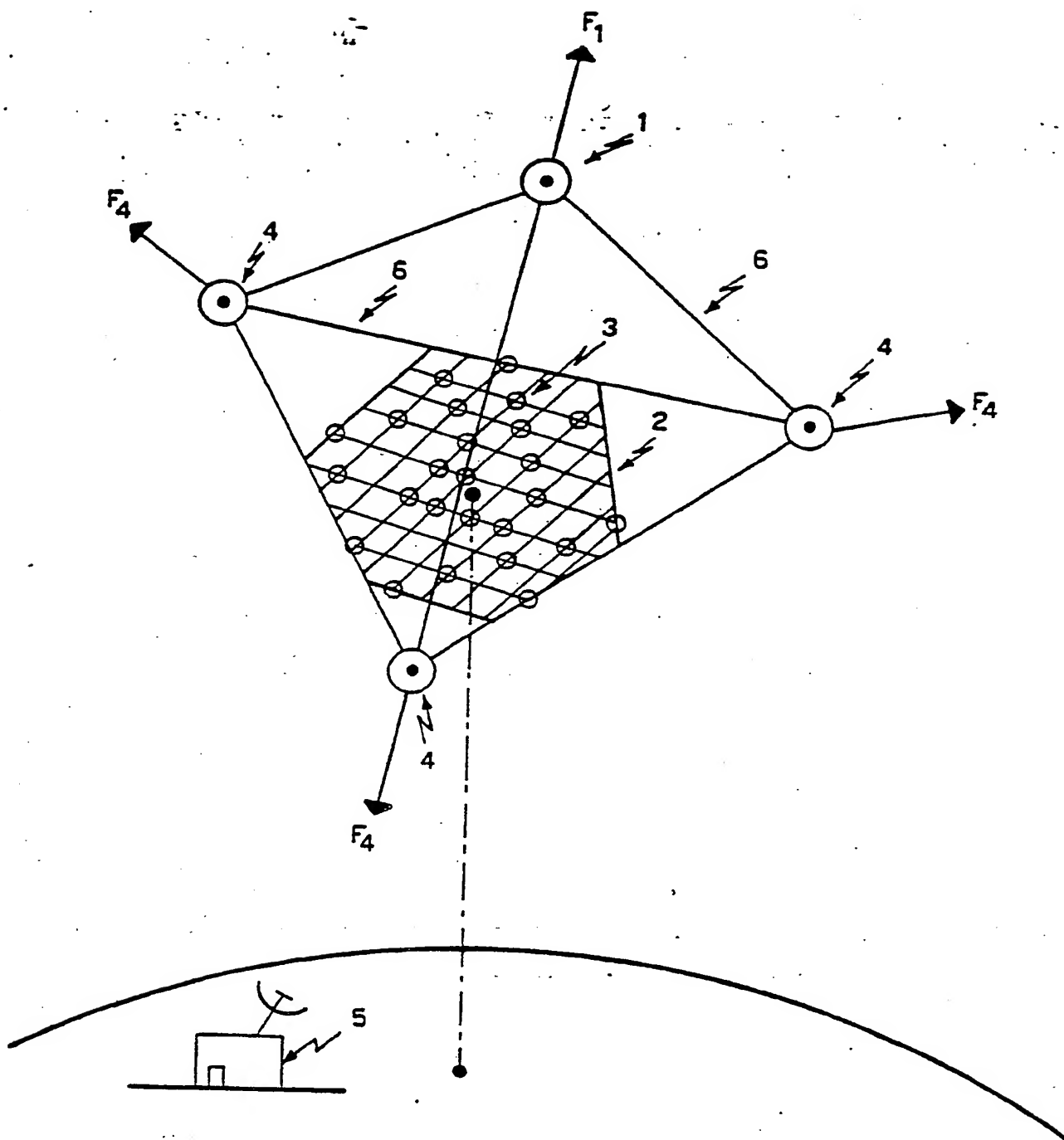


FIG. 2

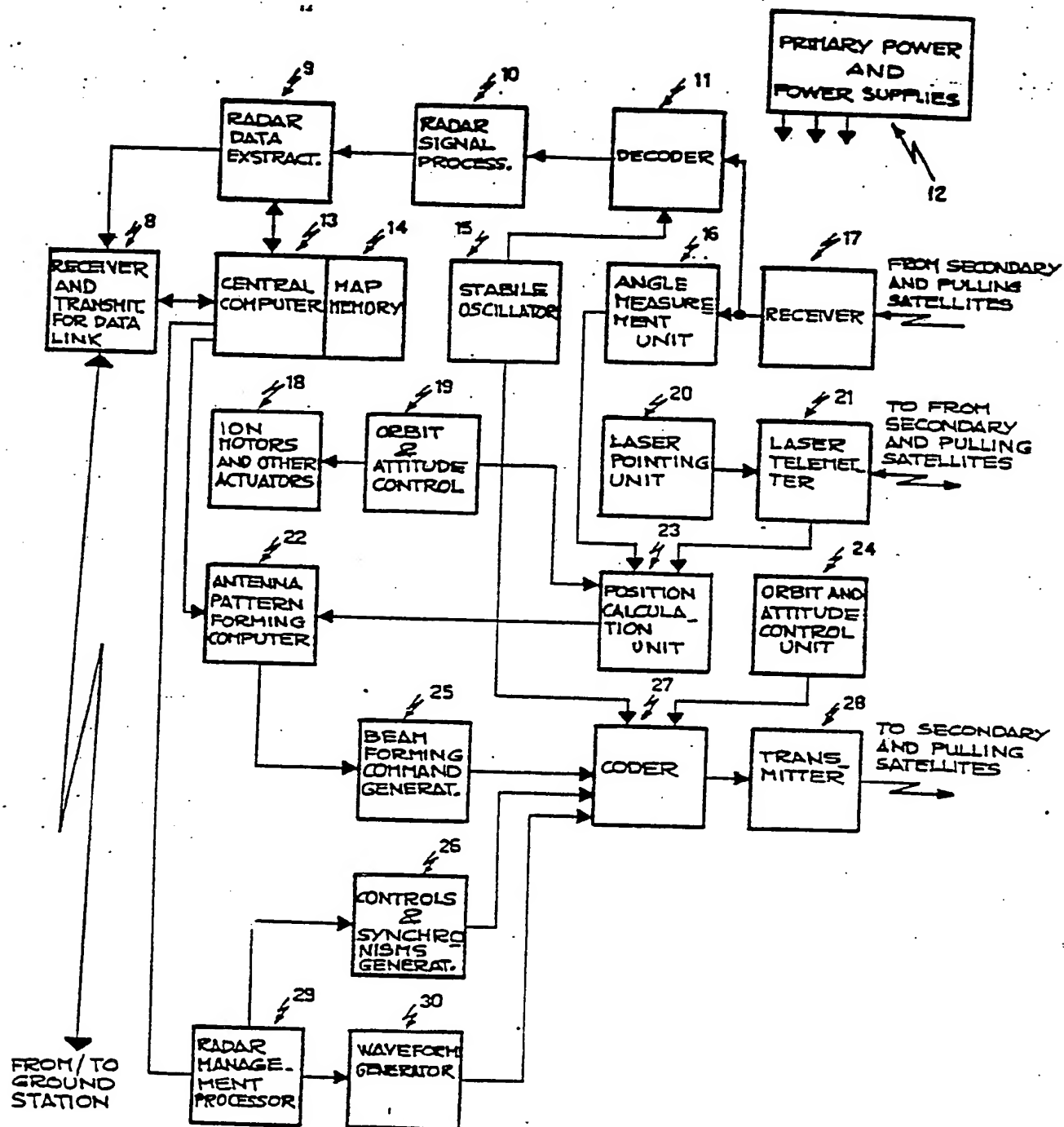


FIG. 3

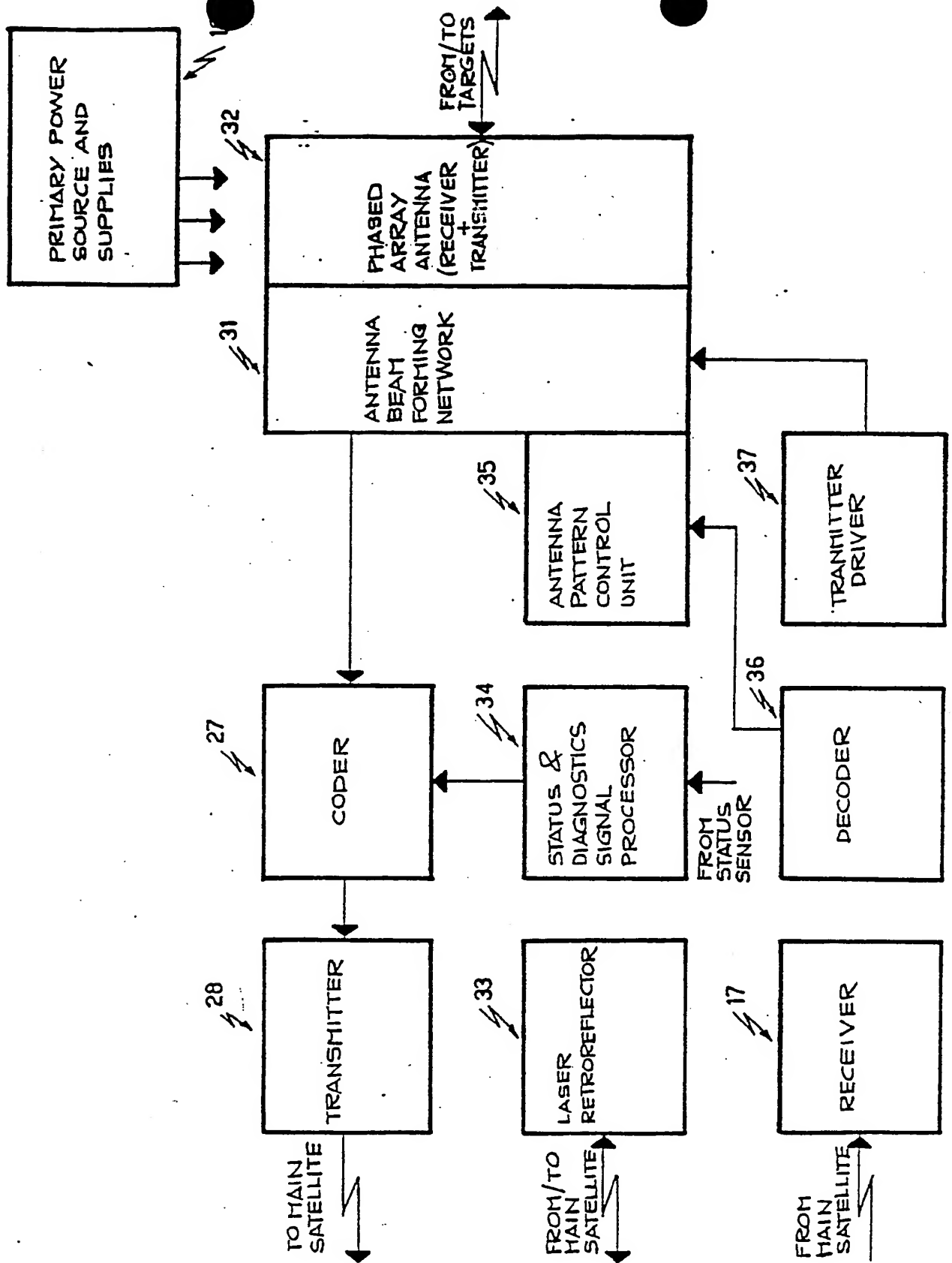


FIG. 4

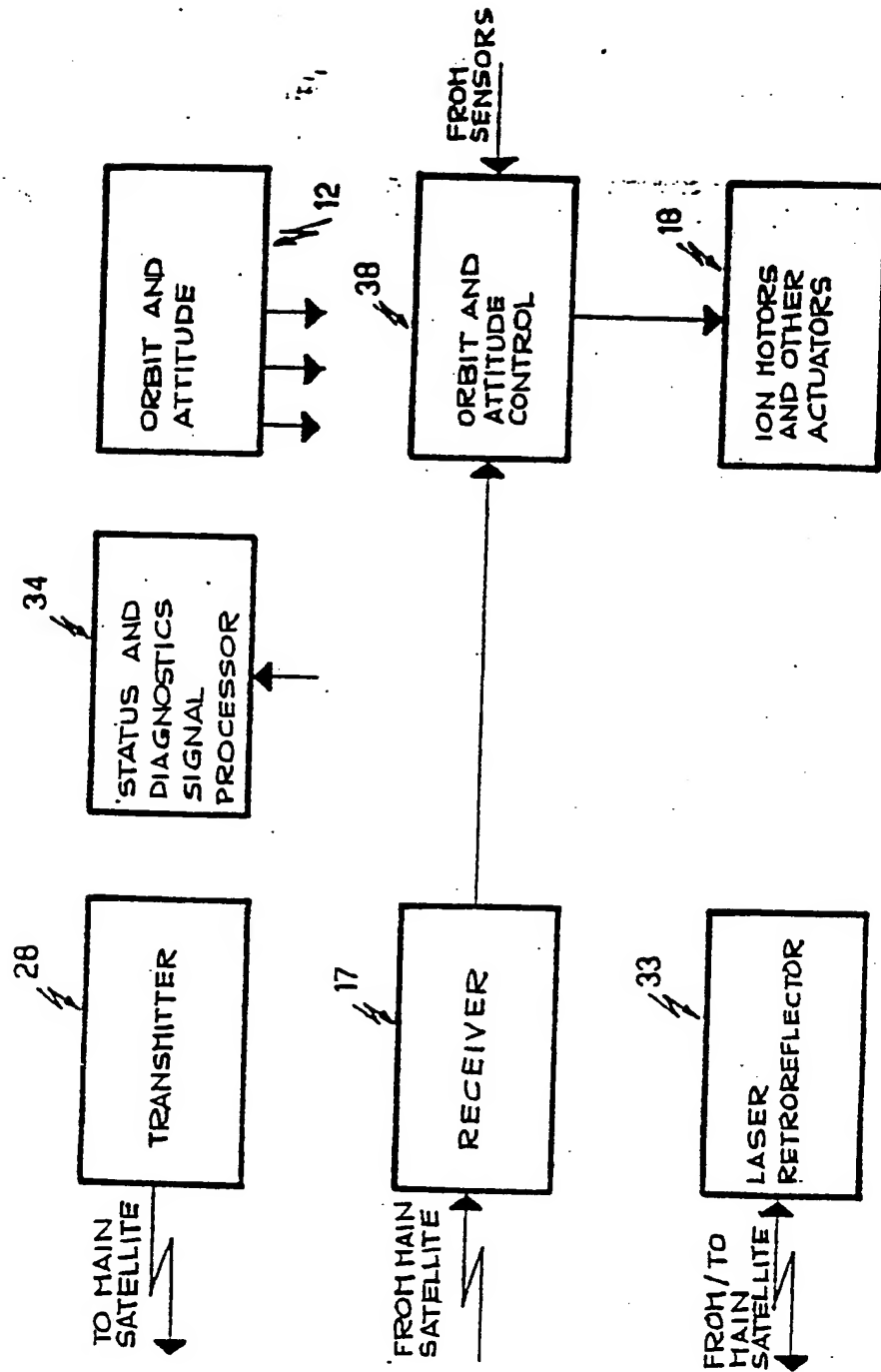


FIG. 5

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(71) Applicant: SELENIA SPAZIO S.p.A.
via Pile 3
I-67100 L'Aquila(IT)

(72) Inventor: Galati, Gaspare
Via C. Corvisieri 22
I-00162 Roma(IT)
Inventor: Lo Squadro, Giacinto
Via Igino Giordani, 60
I-00155 Roma(IT)

(74) Representative: Gustorf, Gerhard, Dipl.-Ing.
Patentanwalt Dipl.-Ing. Gerhard Gustorf
Bachstrasse 6 A
D-8300 Landshut(DE)

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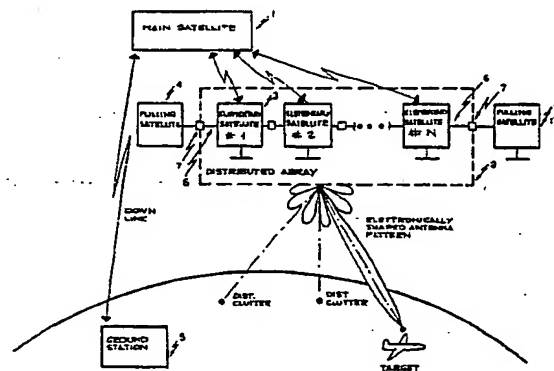


FIG. 1

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European Patent
Office

EUROPEAN SEARCH REPORT

Application Number

EP 88 10 4767

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.4)
X	PROCEEDINGS OF IGARSS SYMPOSIUM, Zürich, 8th-11th September 1986, pages 697-701, Paris, FR; M.S. KAPLAN: "Application of spaceborne distributed aperture/coherent array processing (SDA/CAP) technology to active and passive microwave remote sensing" * Whole document *	1	G 01 S 13/42 G 01 S 7/02 B 64 G 1/00
A,D	IEEE TRANSACTIONS ON AEROSPACE AND ELECTRONIC SYSTEMS, vol. AES-19, no. 6, November 1983, pages 831-839, New York, US; R.C. HEIMILLER et al.: "Distributed array radar" * Pages 831-834, paragraphs I,II; page 838, paragraph IV; figures 1-4 *	1	
A	US-A-4 163 235 (J.L. SCHULTZ) * Whole document *	1,2	
A	GB-A-2 134 353 (BRITISH AEROSPACE) * Page 1, lines 5-70; abstract; figure 2C *	1	TECHNICAL FIELDS SEARCHED (Int. Cl.4)
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The present search report has been drawn up for all claims			
Place of search THE HAGUE		Date of completion of the search 15-03-1990	Examiner VAN WEEL E.J.G.
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